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Title: Physical Acoustics Characterization For Inspection and Evaluation

Author(s): Ulrich, Timothy James II
Remillieux, Marcel
Beardslee, Luke Berny
Le Bas, Pierre-Yves

Intended for: Share slides from internal workshop with external colleagues.

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Physical Acoustics Characterization For Inspection and Evaluation

Weapons Focused Additive Manufacturing Workshop

TJ Ulrich (Q-6)

Marcel Remillieux (EES-17)

Luke Beardslee (EES-17)

Pierre-Yves Le Bas (Q-6)

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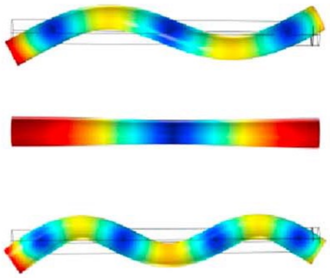
Physical Acoustics Characterization (PAC)

- The area of acoustics and physics that studies interactions of acoustic waves with gaseous, liquid and/or **solid** media on ***macro-*** and ***micro-*** scales … to *obtain the relevant information about a medium under consideration by measuring the properties of acoustic waves* propagating through this medium. -- *Wikipedia*
- Properties controlling waves:
  - Material properties (i.e., elastic properties, mass density)
  - Geometry (e.g., exterior shape, internal defects)
  - Boundary conditions
- Uses two main wave modalities:
  - Propagating waves, i.e., transients
  - ***Standing waves, i.e., resonance***

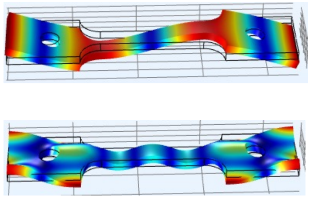
Standing Waves (Resonance)

- A **standing wave**, also known as a **stationary wave** or a **resonance**, is a wave which oscillates in time but whose peak amplitude profile does not move in space.
- Resonance occurs in objects at distinct frequencies, known as resonance frequencies defined by the shape of the object, stiffness of the material, and boundary conditions (e.g., fixed vs. free).
- Standing wave patterns (i.e., vibrational shape) are known as resonant modes.
- Example modes:

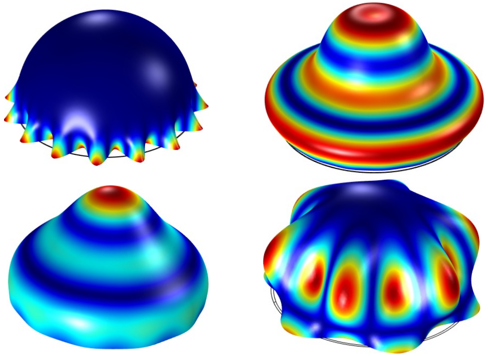
Cylindrical Rod



"Dog bone"



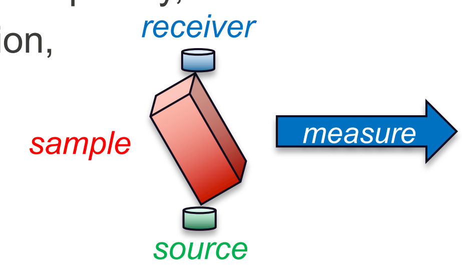
Hemispherical shell

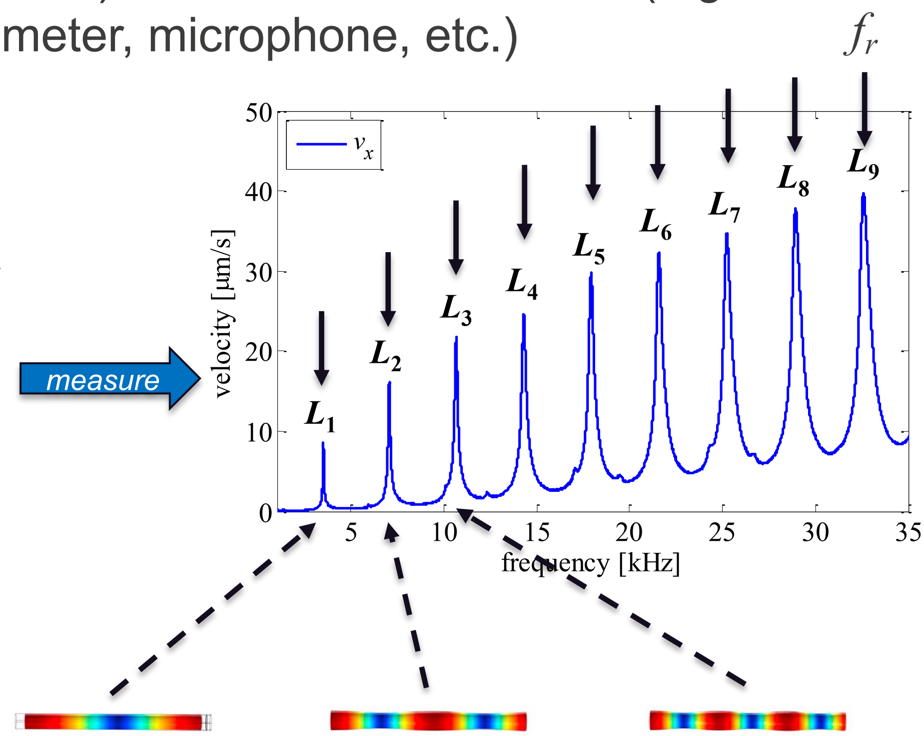


Measuring Resonance

- Making resonance measurements requires a source of vibration (e.g., controlled transducer, operational noise, etc.) and a vibration detector (e.g., piezo-electric accelerometer, laser vibrometer, microphone, etc.)

- Resonance Spectrum (typical):
  - excite source transducer at single frequency,
  - measure response at single location,
  - increment source frequency,
  - repeat.



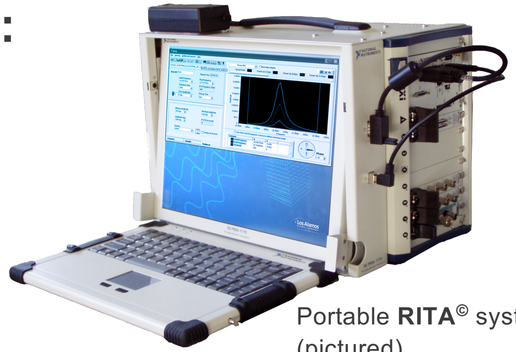


- Resonant Modes:
  - Excite at a resonance frequency
  - Measure response at multiple locations
    - Typically use scanning laser vibrometer

Resonance Inspection Techniques & Analyses (RITA©)

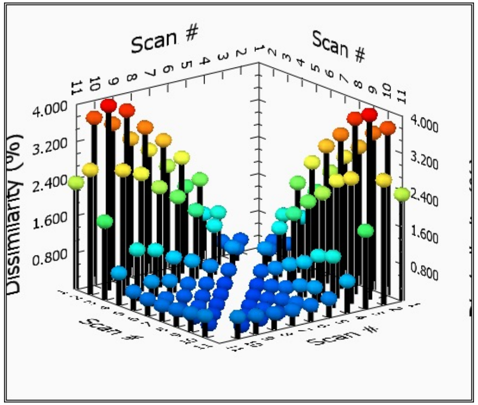
Using vibrational resonant response of a structure for:

- ARS: Acoustic Resonance Spectroscopy for signature identification and "finger-printing"
- RUS: Resonant Ultrasound Spectroscopy for measuring material properties (elastic constants, density)
- NRUS: Nonlinear RUS for damage detection & quantification



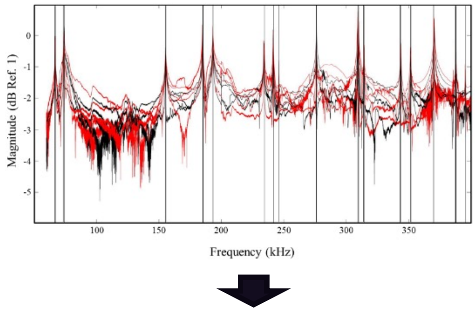
Portable **RITA©** system (pictured).

ARS



Quick sorting of parts

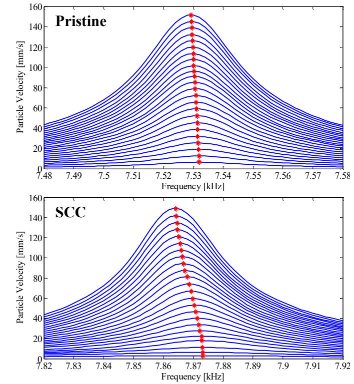
RUS



Material properties (moduli, wave speeds, density)

$$C_{ijkl}\,,\ v_{L,S}\,,\ \rho$$

NRUS

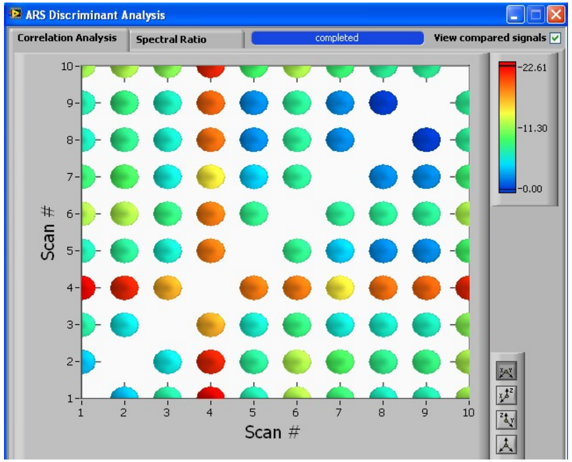


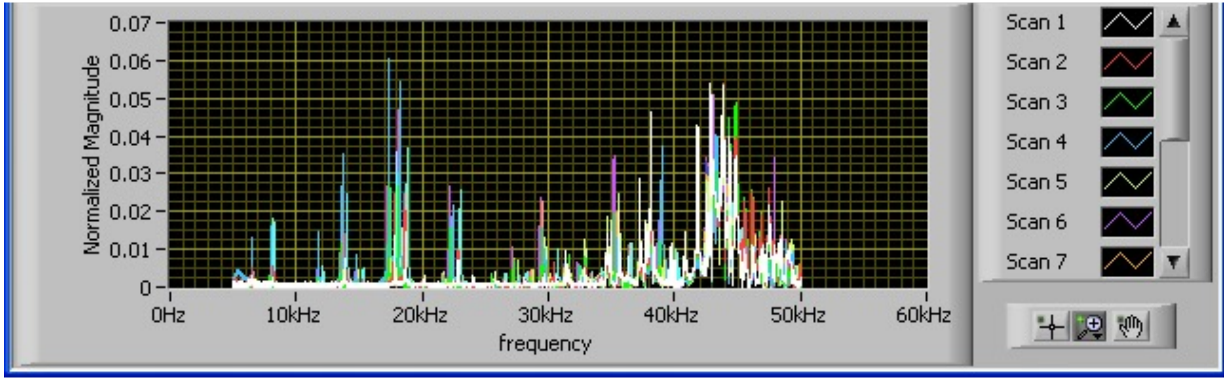
Material Integrity Quantification and Damage Monitoring

Acoustic Resonance Spectroscopy
(“Finger Printing”)

ARS: Description of the Technology

- Resonances are uniquely determined by geometry, mass density, and elastic tensor.
- Compare resonance spectra to identify changes in the above parameters.
- Use machine learning to automate identification and process large data sets.

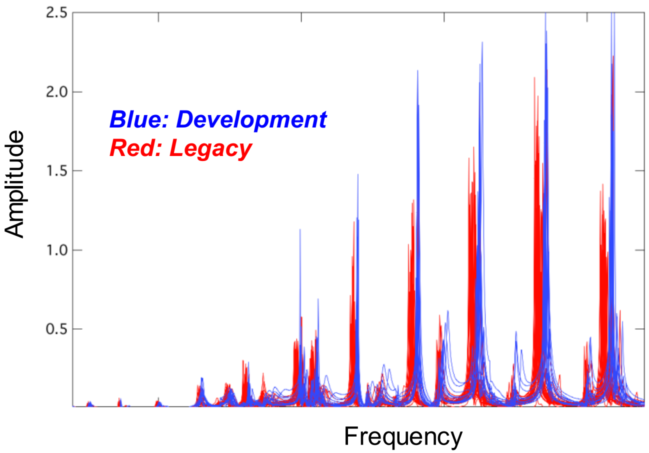


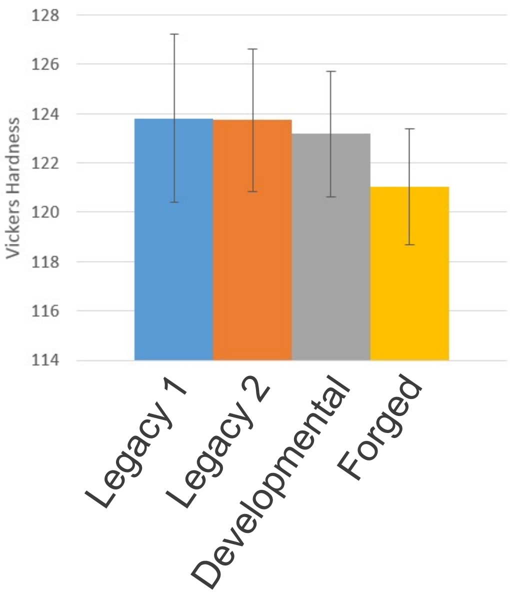


ARS Example: Legacy vs. Development Components

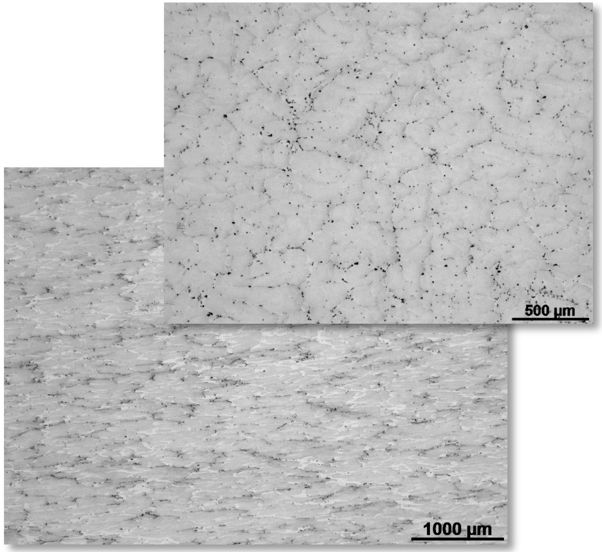
- High tolerance on geometry: verified no geometrical differences
- Destructive Testing 1: Hardness; within the error bars, no differences really
- Destructive Testing 2: grain structure; obvious differences that ARS was able to detect

RITA (ARS) nondestructively detected differences



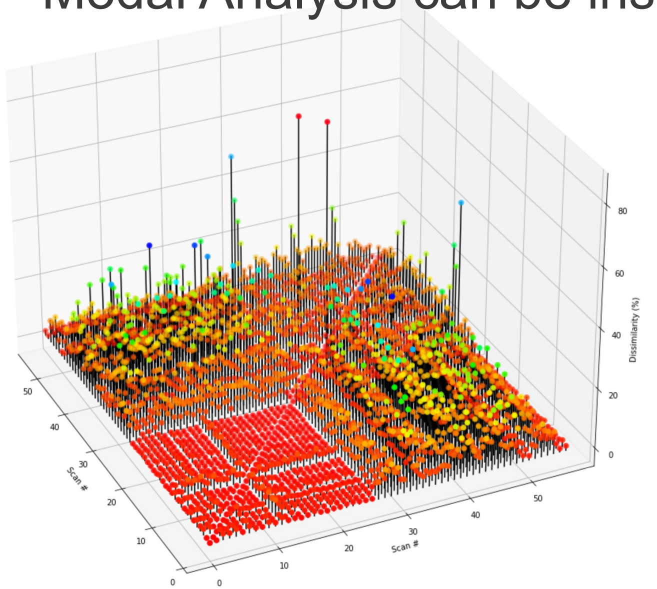


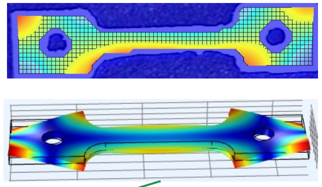
Developmental process resulted in different microstructure

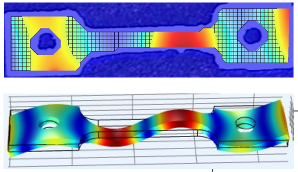


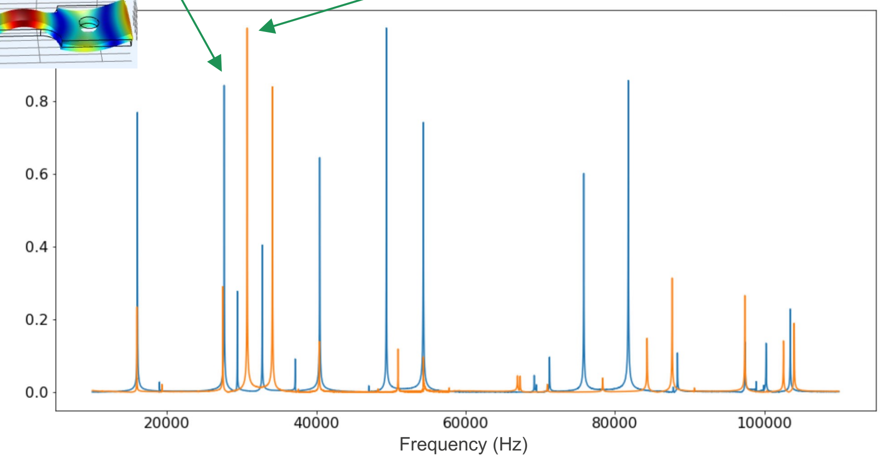
ARS Example: Additively Manufactured Components

- AM dog bone specimens for mechanical testing
- 57 samples analyzed blindly
- 27 samples are self consistent
- Remaining samples indicate considerable variation
- Modal Analysis can be insightful, but not quantitative.









Resonant Ultrasound Spectroscopy (Quantification of Properties)

RUS: Limitations of Traditional Methodology

- Simple geometries (solid spheres, right circular cylinders, rectangular parallelepipeds) required for “forward” calculation of resonance frequencies.
- Free boundary conditions, minimal coupling/impact of source and receiver transducers.
- Rule of thumb: 5 resonance frequencies needed for each independent elastic constant (e.g., 2 constants for isotropic = 10 resonance peaks)
- Must capture lowest resonance frequencies, no missing modes allowed. (exceptions allow a few missing modes, but must know where)
- Inversion process typically requires initial “guess” of elastic constants to be close to actual values.

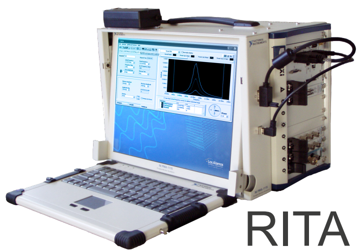
Material Property Determination of Complex Geometries

Complete Process:

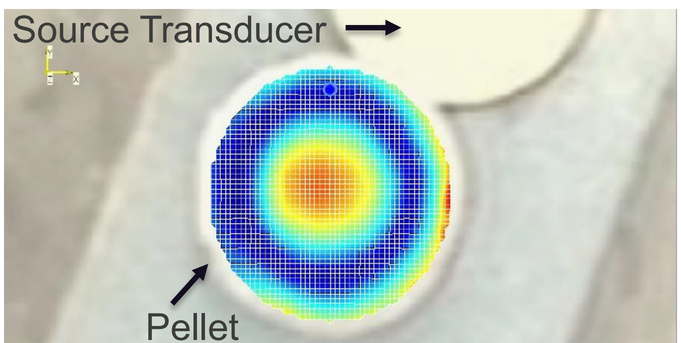
- **Resonance Measurement**: Vibrate component and utilize 3D laser vibrometry to:
  - Measure resonance frequencies
  - Image modal shapes
- **Component Geometry Measurement**:
  - 3D Geometry Scan of Part (Faro Arm, CMM)
  - Post Process 3D Geometry Scan
- **COMSOL Analysis:** FEM using 3D geometry from Faro Arm
  - Compute expected resonance frequencies
  - Visualize expected resonance modes
- **Data Interpretation (Mode Matching)**: match resonance frequencies from LV measurements (frequencies and shapes) to results from COMSOL
- **Material Property Determination (RUS Inversion)**: using specified frequencies from mode matching, geometry from Faro arm measurements and the COMSOL model, iteratively solve for the properties (***elastic moduli, density, Euler angles***) using a genetic algorithm.

RUS on new PETN Mock: Material Property Determination

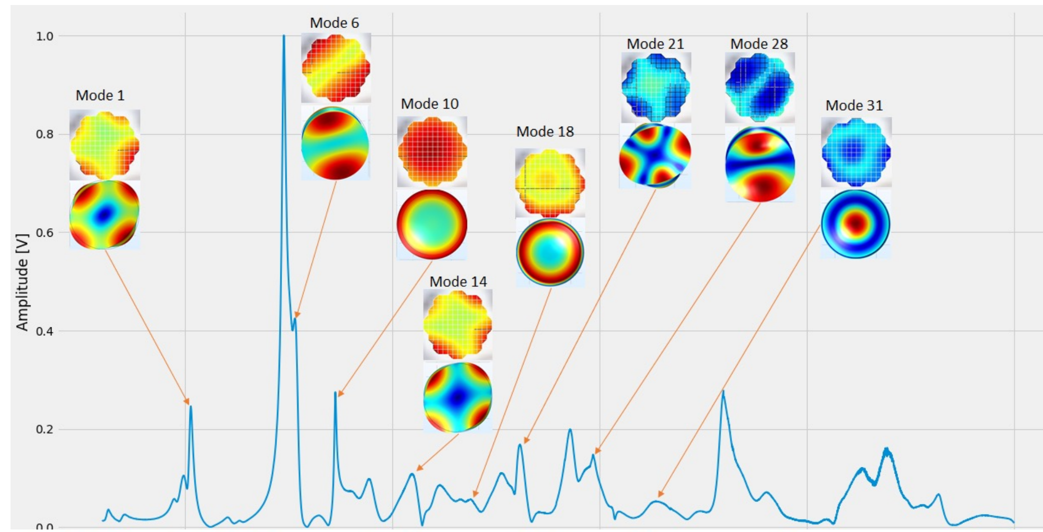
3D Laser vibrometer (receiver)



RITA



Pellet (with modal response from 3D SLDV overlaid)

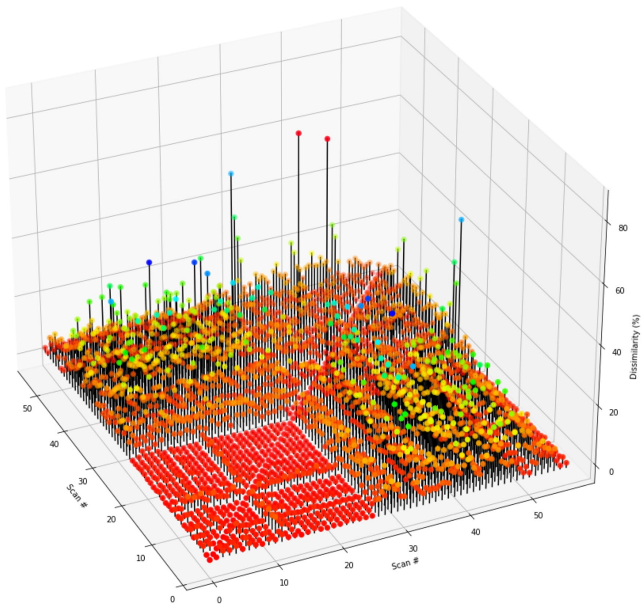


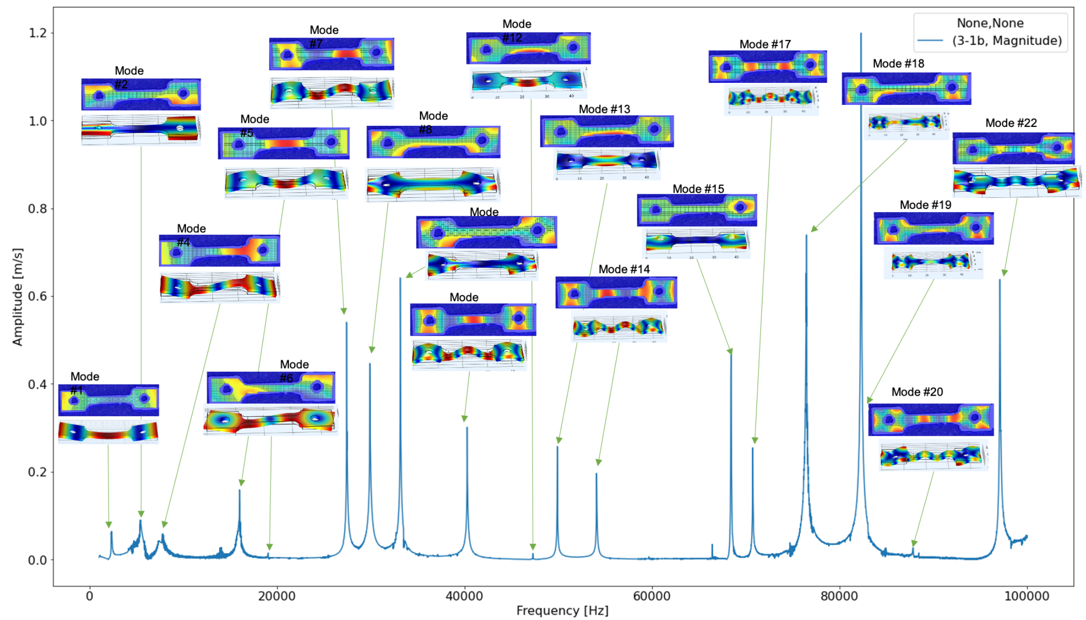
C11 (GPa)	C44 (GPa)	E (GPa)	Nu	Density (kg/m^3)	Error
6.24	1.31	3.59	0.367	1154.0	0.30181%

RUS Example: Complex Geometry, AM Dog Bones

- AM dog bone specimens for mechanical testing
- 57 samples analyzed blindly
- 27 samples are self consistent
- Remaining samples indicate considerable variation

Origin of the differences?

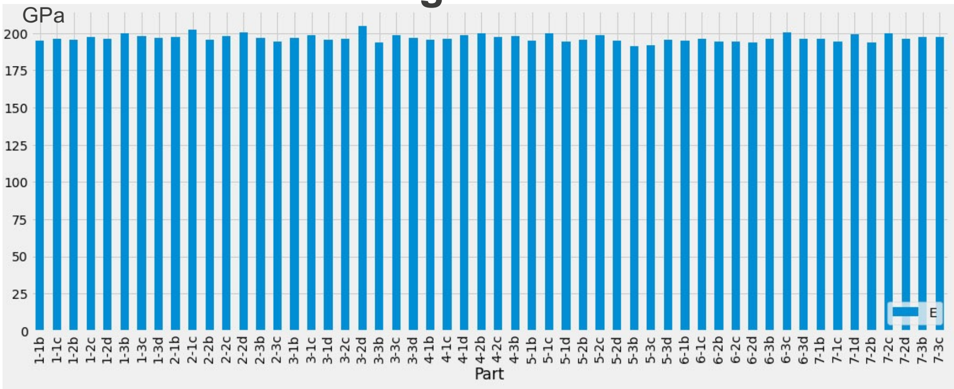




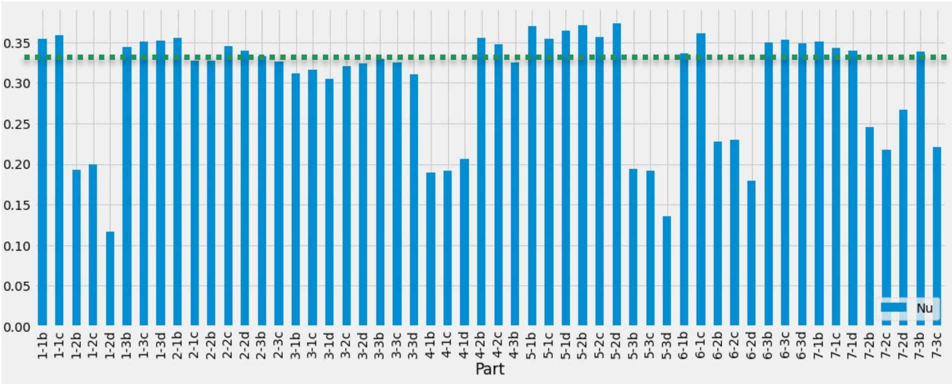
RUS Example: Complex Geometry, AM Dog Bones

- Utilize FEM based RUS methodology with resonance mode matching.
- Results:
  - All parts have essentially the same Young's Modulus.
  - Self consistent parts have typical Poisson's ratio of >0.33.
  - Inconsistent parts have varying Poisson's ratios < 0.33
  - Mass density fluctuations < 1%

Young's Modulus



Poisson's Ratio



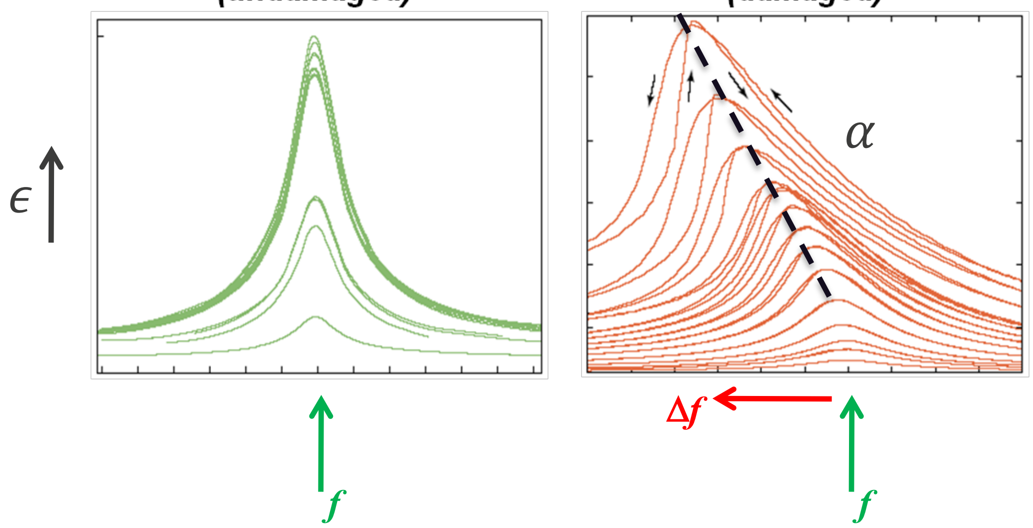
Nonlinear Resonant Ultrasound Spectroscopy (Defect Detection and Quantification)

Nonlinear Resonant Ultrasound Spectroscopy (NRUS)

- Quantify hysteretic nonlinear elastic parameter (α) from the natural resonances (f, Δf) of an object driven at multiple strain (ε) amplitudes.

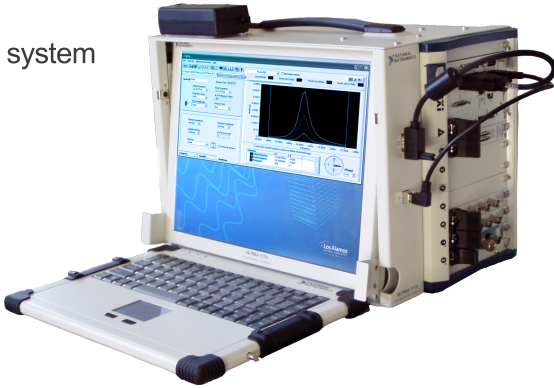
$$\frac{\Delta f}{f} = \alpha\epsilon$$

Linear (undamaged) ***Nonlinear (damaged)***



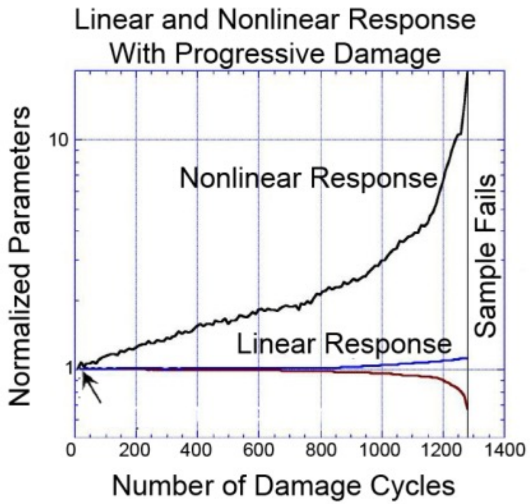
Resonance Inspection Techniques & Analyses (RITA) system previously developed for testing of weapons components.

Portable **RITA**© system (pictured).



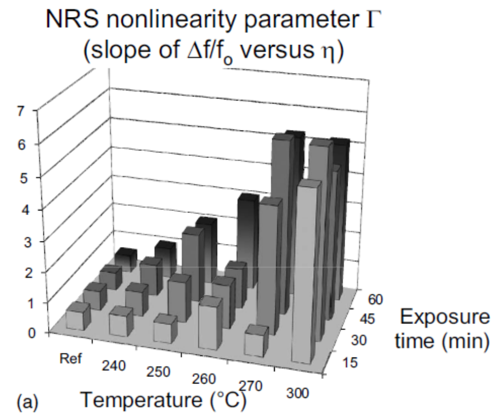
NRUS: Benefits for Damage Detection

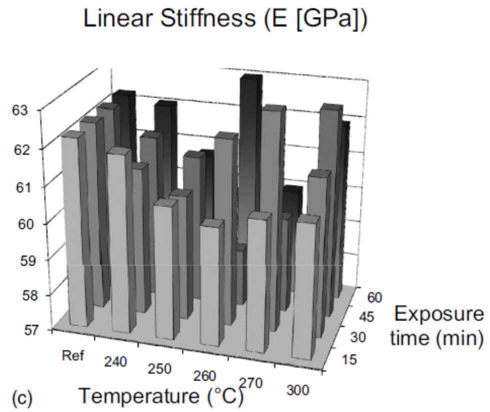
- It has been demonstrated that nonlinear acoustics (including NRUS) is much more sensitive to the presence of damage than linear acoustic techniques.



Normalized evolution of wave-speed (red), linear attenuation (blue) and nonlinearity (black) of a plastic sample subjected to fatigue loading.

- In fact, nonlinear indicators correlate directly with damage density.



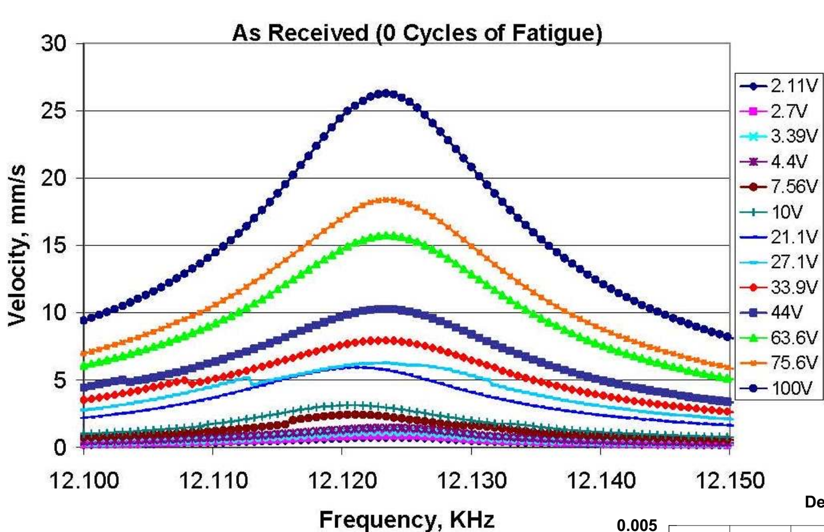


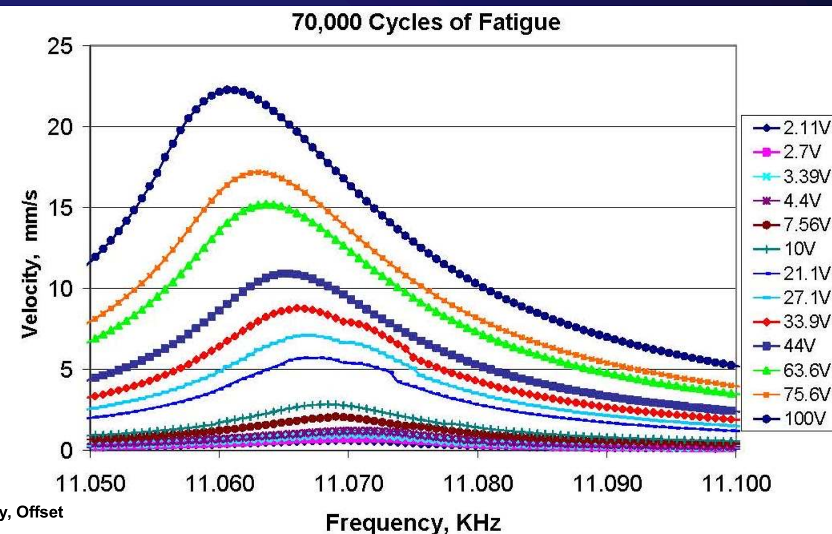
Evolution and quantification of damage in a composite plate

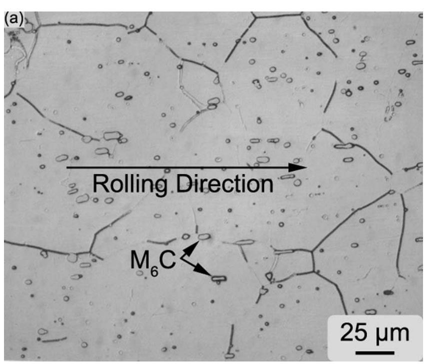
NRUS Example: fatigue damage in Haynes 230 Superalloy

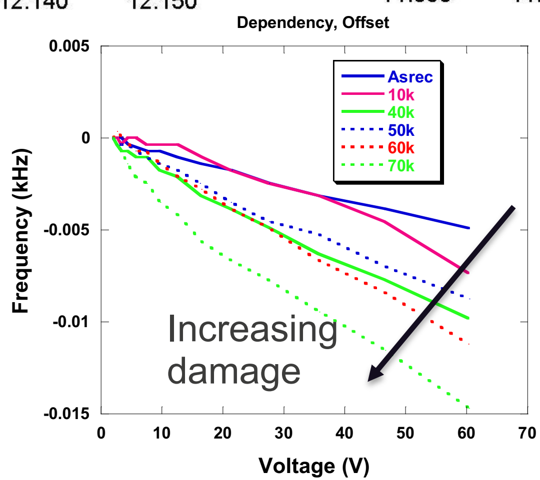
Nondestructive Evaluation of Loading and Fatigue Effects in Haynes® 230® Alloy

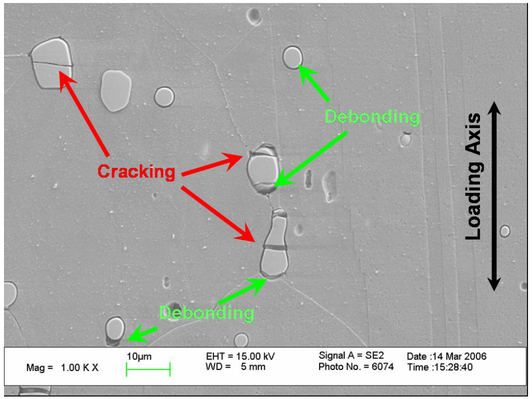
TA Saleh - 2006







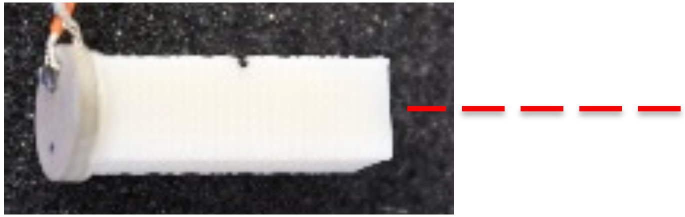




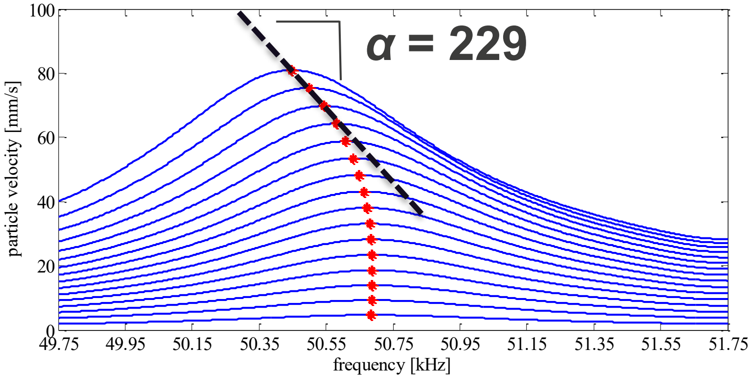
NRUS Example: AM of ABS plastic components

- Tested 4 AM samples(square columns 10mm X 10mm X 30mm).
- Samples were instrumented with piezoelectric transducers.
- The vibrational response of the longitudinal modes of the samples was measured on the side opposite to the transducer using a LASER vibrometer.

Experimental Setup



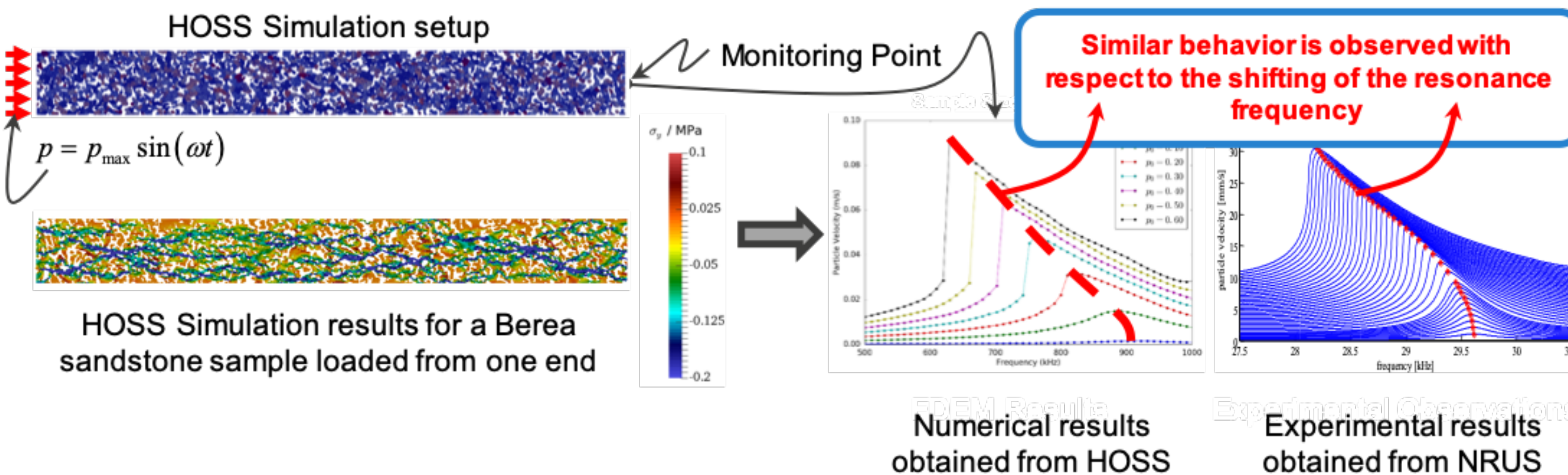
Blind test accurately revealed 1 of the 4 samples to be defective from the quantification of α.



Nonlinear elastic material analysis - meso-scale mechanics

Experimental (NRUS) vs Numerical (HOSS)

- **A cross section of granular material was obtained and its grain structure was incorporated into HOSS**



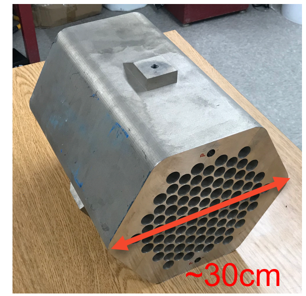
- The simulations established a direct link between nonlinear elastic behavior and force chains inside the sample.
- Without the force chains (i.e., without porosity) the non-linear elastic behavior **is not** observed.

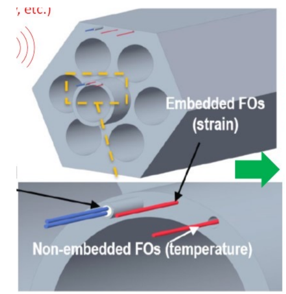
Current Activities & Path Forward

Current Projects

- LDRD
  - ER Reserve: apply acoustic monitoring (including resonance techniques) to SMR components
    - use embedded sensing (fiber Bragg)
    - use ambient noise

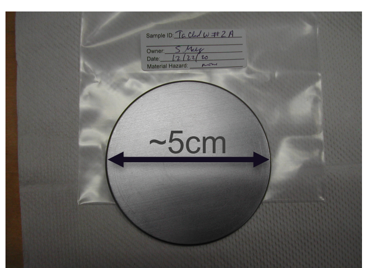
AM stainless steel

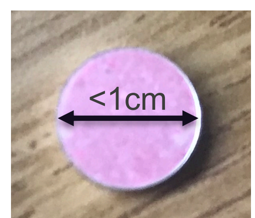




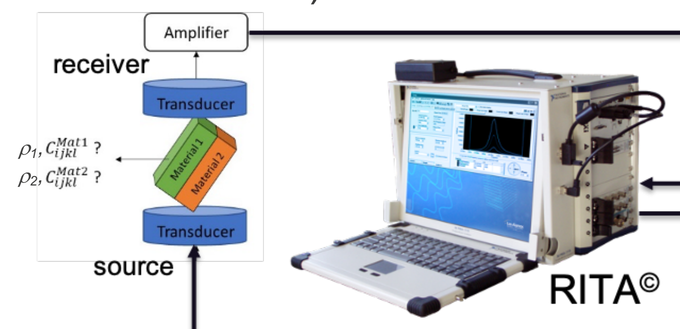
  - DI (through Seaborg Institute): Enhance RUS for Composite Samples
    - multiple materials (e.g. bonded samples of more than one material)
    - in situ boundary conditions (e.g., fixed vs. free)

Ta, W, Ta sandwich

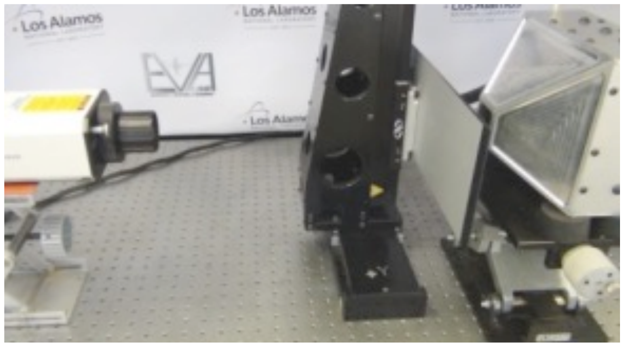


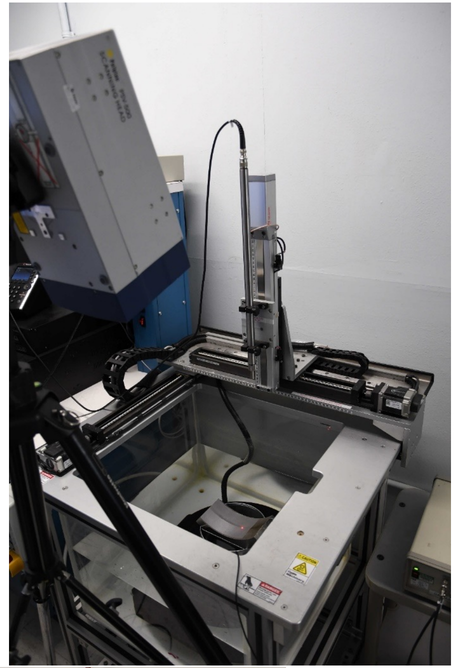


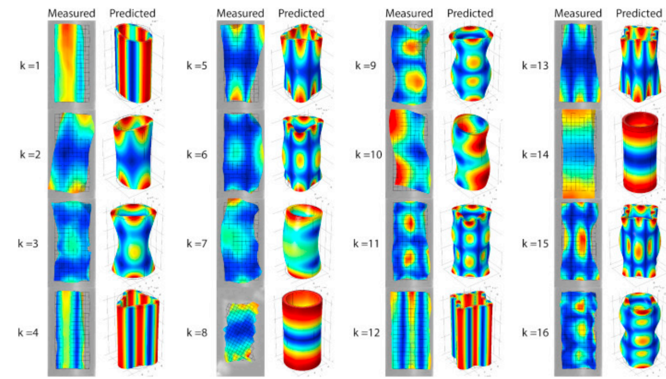
HE in Al cup



Questions?






Measured
Predicted
k =1
k =2
k =3
k =4
k =5
k =6
k =7
k =8
k =9
k =10
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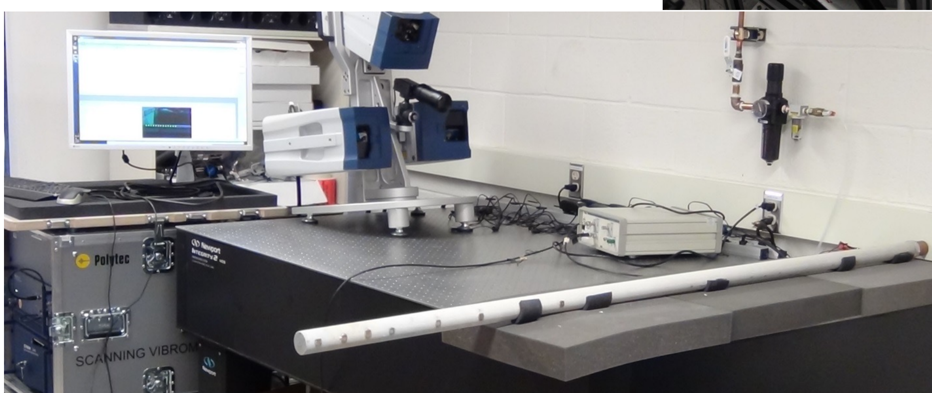
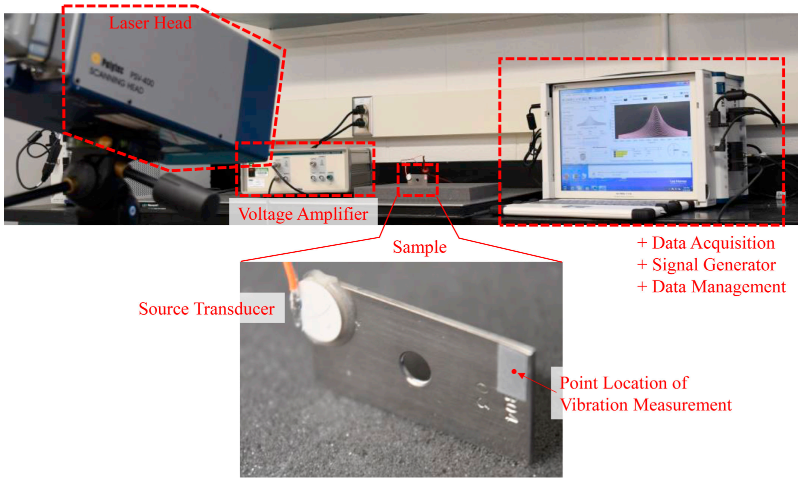
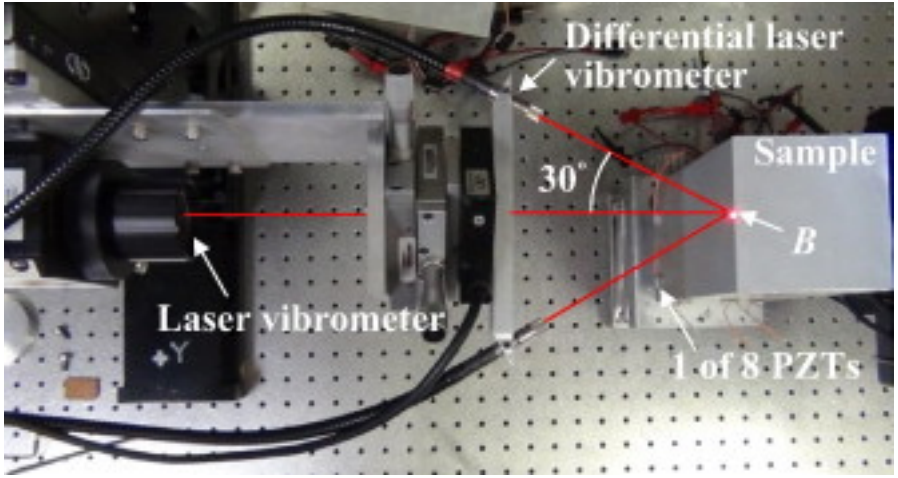
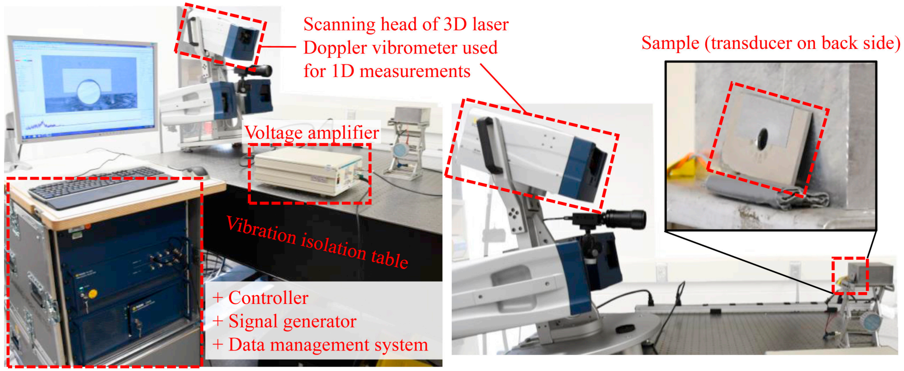
k =12
k =13
k =14
k =15
k =16

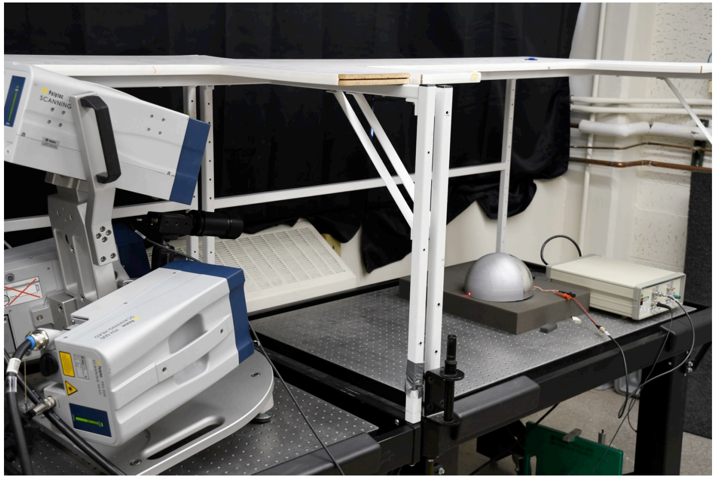

Polytec

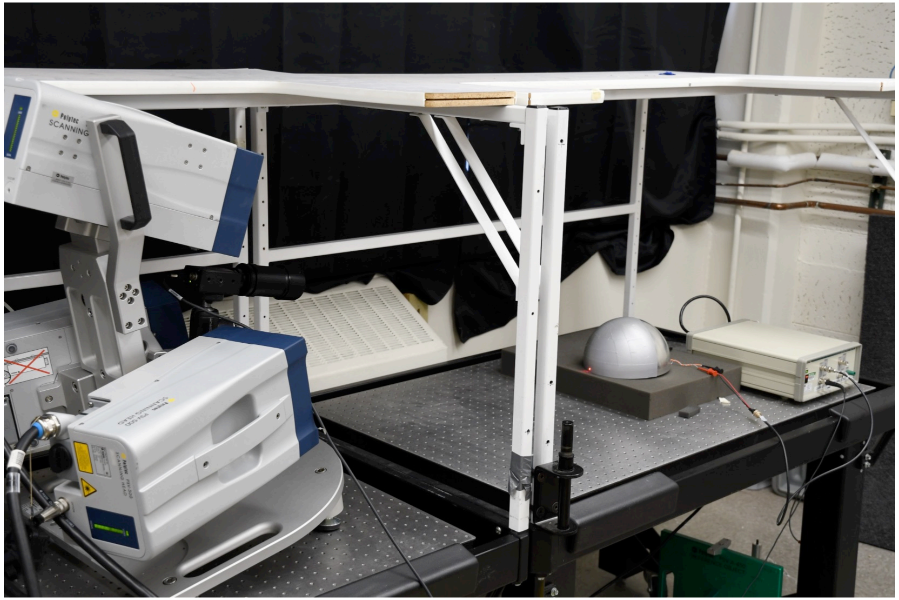

A
data acquisition
sample
vibrometer
amplifier
B


Laser Head
Voltage Amplifier
Sample
+ Data Acquisition
+ Signal Generator
+ Data Management
Source Transducer
Point Location of
Vibration Measurement


Differential laser
vibrometer
Sample
30°
B
Laser vibrometer
+Y
1 of 8 PZTs


Scanning head of 3D laser
Doppler vibrometer used
for 1D measurements
Sample (transducer on back side)
Voltage amplifier
Vibration isolation table
+ Controller
+ Signal generator
+ Data management system




Polytec
SCANNING